Net and Tension Infiltration Effects of PAM in Furrow Irrigation

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The history and fundamental aspects of polyacrylamide (PAM)-use in furrow irrigation water has been covered in depth in several publications *(Barvenik, 1994; Lentz et al., 1992; Lentz and Sojka, 1994a; Lentz, 1995; Lentz and Sojka, 1996; Sojka and Lentz, 1996; Sojka and Lentz, 1997)*. In agriculture, the two greatest benefits associated with this practice are the near elimination of furrow erosion and substantial increases in infiltration compared to untreated water. The large erosion reduction has both on-site and downstream economic and environmental benefits *(Agassi et al., 1995; Bahr et al., 1996; Bahr and Steiber, 1996; Lentz et al., 1992; Lentz, 1995; Lentz and Sojka, 1996; McCutchan et al., 1993; Singh et al., 1996; Sojka and Lentz, 1993; Sojka and Lentz, 1994b; Sojka et al., 1995; Sojka and Lentz, 1997)*. Infiltration effects are a substantial aspect of these benefits, but have been less thoroughly considered in data reported to date.

The motivations driving adoption of PAM-use have been related to three factors:

1) farm operational and/or economic benefits associated with reducing furrow irrigation-induced erosion,

2) environmental altruism and/or need to meet or avoid imposition of water quality standards for sediments, pesticides, and nutrients in return flow receiving waters, or

3) need for increased water intake and/or other water management needs and constraints driven by water cost or availability and/or crop-stress avoidance to safeguard yield and/or quality (and hence value) of the crop produced. On fine-textured soils, water intake can be a more compelling factor than erosion or pollution prevention.

In examining factors governing PAM-effects on infiltration, two fundamental aspects of PAM's mode of action in irrigation water should be considered. First, PAM acts by influencing soil water processes at the immediate soil surface (the soil-water interface). To the extent that infiltration is governed by subsurface conditions or phenomena, PAM-use in irrigation water cannot affect changes, other than to sometimes alter the timing of expression or onset of these subsurface factors during the course of an irrigation set. Second, PAM is a stabilizing agent. It stabilizes soil structure in its zone of activity near the soil surface, but it cannot create soil structure. A minor exception to this caveat is its formation of floccules from sediments carried in irrigation water. As these floccules settle on the furrow bottom they provide a relatively pervious structure compared to surface seals that form on the wetted perimeters of furrows irrigated with untreated water.

To date, the greatest interest in PAM-use in irrigation water has been for furrow irrigation. Prior to the work begun in 1991 by the USDA-Agricultural Research Service, in Kimberly, ID *(Lentz et al., 1992)* very little PAM research specifically for furrow irrigation had been undertaken or published. The earliest report we have found *(Paganyas, 1975)* described reduced furrow irrigation erosion in cotton, using furrow pretreatment with water soluble polymers. Unfortunately the report did not specify the nature of the compounds, referring to them only as "K" compounds. The description of the K compounds was vague but suggested a polyacrylamide copolymer of some kind.

Mitchell (1986) PAM-treated furrow irrigation water to investigate infiltration on Holtville silty clay (clayey over loamy, montmorillonitic, calcareous, hyperthermic Typic Torrifluvents) a cracking clay soil. PAM was applied in the advance water (only) at 2.5, 5, and 15 times the current NRCS standard *(Anonymous, 1995)* of 10 ppm, using a PAM similar to ones currently used. At first inspection Mitchell presents what appear to be contradictory data for PAM-use, namely increased infiltration and more rapid stream advance compared to controls. He reported a 30 to 57% increase in initial infiltration rate, measured immediately after completion of advance. At irrigation's end, however, infiltration rates of treated and untreated plots were similar. Data were not shown, but based on final soil profile water content measurement, there was no net infiltration difference between treatments. The initial infiltration rate increase and faster advance can be reconciled by examining viscosity effects and the timing of infiltration rate measurements relative to onset of seal formation in the system.

At Mitchell's high PAM rates, the briefer advance times with PAM application, were attributed to increased viscosity of the water *(Malik and Letey, 1992)*, reducing infiltration during the advance (Note: this is the opposite of what has been consistently observed with 10 ppm PAM; the 10 ppm PAM-rate does not raise viscosity enough to overcome advance-phase infiltration rate increases that result from surface seal prevention). Seal formation in control furrows is a rapid process. Apparently, PAM viscosity effects lowered infiltration enough during advance to raise runoff rate (greater effective stream size along the furrow) compared to controls. Thus, during the advance, water infiltration into controls was at a high rate. However as the advance proceeded in control furrows, surface sealing occurred rapidly in the wake of the stream advance. By the time runoff began from control furrows, seal formation in the controls was more restrictive to water entry than the viscosity effects in the PAM-treated furrows (which prevented seal formation). Thus the infiltration rate trends at the time of their measurement were probably the reverse of the trends that determined the advance rates. Soil erosion was not measured, but with PAM, clear runoff and elimination of dispersion and slaking was noted.

Lentz et al. (1992) published the first detailed report of the effects of PAM-treatment of furrow irrigation water on advance, net-infiltration, furrow infiltration rate, runoff rate, runoff amount, sediment loss, sediment loss rates and sediment concentration changes. These parameters were measured in a series of furrow treatments using PAM rates from 5-20 ppm applied in a number of application strategies, including the NRCS recommended strategy of treating the water advance (only) with 10 ppm PAM. The success of these treatments at halting furrow irrigation-induced erosion at very low PAM rates (typically about 1 kg/ha per treated irrigation) stimulated NRCS interest in PAM-use and prompted related field studies by several other research teams. These results and those of several subsequent studies are summarized in this paper to provide a more comprehensive assessment of PAM's effects on furrow infiltration phenomenon.

Methods and Materials

The results discussed were obtained from a series of studies conducted from 1991 through 1995 at or near the USDA Agricultural Research Service's Northwest Irrigation and Soils Research Laboratory in Kimberly, Idaho. Soils included Xerollic Haplargids and Haploxerollic Durargids, but most studies were on Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthids). Surface horizons and physical and chemical characteristics of all soils were similar. Textures were silt loams (10-21% clay, 60-75% silt). Organic matter ranged from 10-13 g/kg. Saturated paste extract EC was 0.7 to 1.3 dS/m, ESP was 1.4 to 1.7, pH was 7.6-8.0 with CaC03 equivalent of 2-8%. Slopes varied from 0.5 to 3.5%, but unless noted otherwise, data generally reflect slopes of 1 to 1.5%.

Water was applied as furrow irrigation (usually either via spigoted plastic pipe or siphon tubes) to conventionally tilled fields, usually disked in autumn and spring, then roller harrowed following incorporation of fertilizer and herbicides prior to planting. Furrows ranged from 175 to 264 m in length; they varied from 10 to 20 cm in depth, depending on crop grown, and were prepared with weighted 75° shaping tools. Furrow spacing varied with crops, which included edible dry beans (*Phaseolus vulgaris*) @ 56 cm, corn (*Zea mays*) @ 76 cm and potato (*Solanum tuberosum*) @ 91.5 cm. Irrigation was normally on every other furrow only (hence 112, 152 and 183 cm between irrigated furrows respectively), usually in wheel-track furrows. Per hectare sediment loss and infiltration were calculated based on the spacing between irrigated furrows. Irrigation water was withdrawn from the Twin Falls Canal Company system and had an electrical conductivity (EC) of 0.5 dS/m and a sodium adsorption ratio (SAR) of 0.4 to 0.7. Net infiltration, runoff, and sediment-loss measurements were accomplished by use of periodic flow monitoring and sampling and automated data analysis similar to methods described in detail elsewhere *(Sojka et al. 1992 and 1994, Lentz and Sojka, 1994b and 1995)*.

Polyacrylamide (PAM) copolymer used, unless noted otherwise, was a dry granular material having an approximate molecular weight of 12-15 Mg/mole, with an 18% negative charge density, manufactured by CYTEC Industries of Wayne, NJ. It is marketed in the US by American Cyanamid Company under the trade name Superfloc 836A. Numerous similar materials, granular, compressed cakes, and high concentrate liquids are widely available world wide. Unless noted otherwise, our most frequent means of application involved preparation of liquid stock solutions of 1200-2400 g/m^3 concentration which were metered into furrow stream flows to achieve a concentration of 10 g/m^3 in the advancing water flow before runoff began. Typical flow rates ranged 13-38 L/min during advance, reduced to 13-23 L/min at initiation of runoff.

One study involved the use of a recirculating infiltrometer in which water was applied to 6-m-long test furrow sections with a recirculating blocked-furrow infiltrometer *(Blair and Trout, 1989; Trout et al., 1995)*. The system continually recycles all sediment that runs off the furrow section back through it, so that the sediment concentration eventually equilibrates at a level equivalent to what occurs at steady state at the end of a long furrow. Flow rates were 18 or 23 L/min. All studies proceeded for eight hours with a control furrow and a PAM-treated furrow running simultaneously.

Another study involved measuring steady state infiltration rates under water tensions of 40 or 100 mm on the morning following an irrigation (approximately 12 hr after irrigation). Measurements used 10 cm diameter disc permeameters described by Cook et al. (1993) and similar to the design of Perroux and White (1988). Each instrument was placed on a bed of fine wet quartz sand (0.1-0.3 mm) contained in 2 cm deep metal rings of 115 mm diameter, pushed 1 cm into the furrow bottom. Six to twelve replicate observations were made in each monitored treatment. Infiltration under 40 mm and 100 mm tension exclude flow through pores larger than 0.75 mm and 0.30 mm equivalent diameter, respectively.

Results and Discussion

Net infiltration in the Idaho field-scale tests was generally increased about 15% when treating furrow advance water with up to 20 ppm PAM *(Lentz et al., 1992, Lentz and Sojka, 1994a)*. Trout et al. (1995), using recirculating infiltrometers, saw infiltration increase 30% on the same soils. In California, McCutchan et al. (1993) reported that 2.5 ppm PAM, continuously applied in furrow irrigation water, did not affect advance time but decreased outflow by 10%; they did not report net infiltration amounts.

The Idaho work of Lentz et al. (1992) and Lentz and Sojka (1994) reported irrigations that varied in duration from 8-12 h. All the data in Lentz et al. (1992) were from the initial irrigation of that season. Lentz and Sojka (1994) reported data from throughout several seasons. Trout et al. (1995) reported data for 8 h irrigations. The soils in the Idaho studies were silt loams with a silica and calcium cemented restrictive layer at about 45 cm in depth. Mitchell (1986) states the irrigations were 12 h or slightly longer in duration on a soil with shrinking and swelling clays on deep profiles capable of root water extraction to 120 cm depth. The soil (Vernalis loam) in the study by McCutchan et al. (1993) was a deep loam with reasonably good aggregation and structure, and data were collected for under seven hours. None of the above studies reported antecedent profile water contents in any detail.

Infiltration rates and net infiltration amounts are affected by soil pore status. The pore status in turn is affected by soil texture and structure, especially at the soil surface, and by soil profile water content and distribution when irrigation is initiated. Early in an irrigation, infiltration rate is most influenced by conditions in the upper profile. Late in an irrigation infiltration is more influenced by conditions deeper in the profile. This is more true in some soils than others, for example, where buried drainage barriers exist, late irrigation intake is greatly impeded. Soils like Portneuf silt loam sustain reasonable infiltration rates even when the profile is saturated. In other soils, loss of a strong potential gradient coupled with a wetting front encountering a zone of low hydraulic conductivity, can significantly reduce infiltration late in an irrigation.

With these considerations in mind, the results from the above studies reflect greater commonality than difference. All point to some improvement of water intake, especially early in the irrigation. Antecedent profile water content determines the water absorption rate and capacity. If an irrigation is shorter, or if the soil profile is drier, infiltration rates will remain higher for a longer proportion of the irrigation set and PAM-treatment of the inflows may have relatively larger net effect. Thus if surface seal differences can influence infiltration rate and net amount infiltrated, the relative differences will be larger in shorter irrigations.

These studies suggest that improved irrigation efficiencies can be had with PAM, where that efficiency is defined as the ratio of water volume stored for crop use to the water volume that must be delivered to the field to achieve that storage. This is particularly true where it is desirable to shorten irrigation set times. This could be either to reduce labor, or to avoid plant stress by reducing the duration of an irrigation set while increasing the frequency of irrigation. Under this consideration, shorter sets facilitate shorter return intervals when irrigating multiple fields from a single water source.

Figure 1. Photograph showing degraded channel and surface seal of untreated furrow on Portneuf silt loam, compared to PAM-treated furrow with 25% wider lateral extent of wetting.

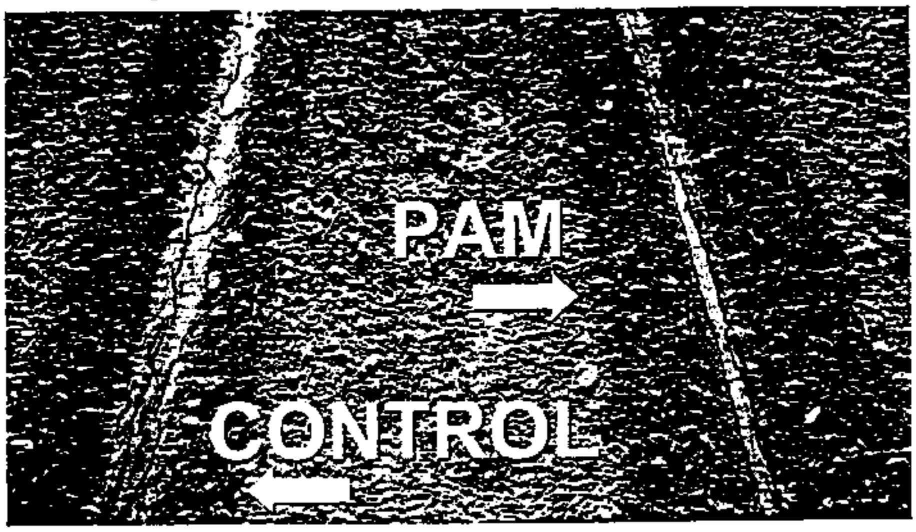
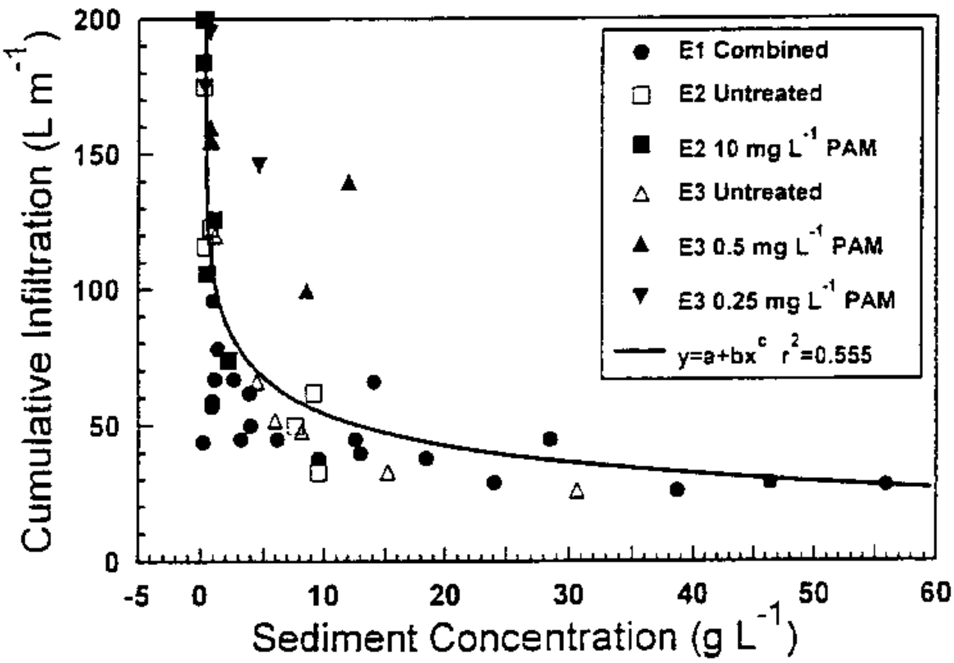
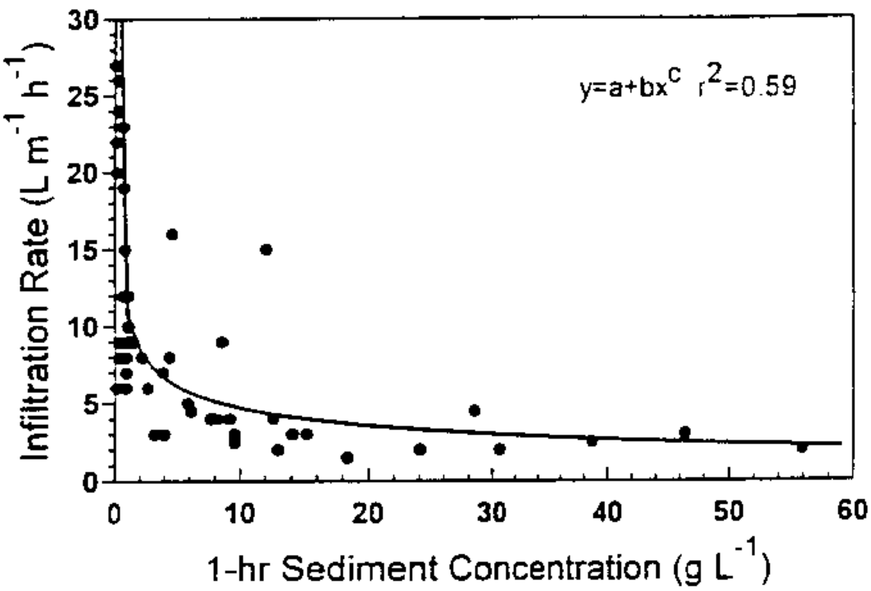


Figure 2. Effect of sediment concentration in furrow water on cumulative infiltration into a Portneuf silt loam as measured over 8 h using a recirculating infiltrometer. Data presented combine several treatment regimes.



PAM's abatement of the furrow erosion process plays a significant role in determining infiltration dynamics. Because PAM-treated furrows do not erode and create a deeper channel, the free water surface is physically higher in elevation in relation to the planted row compared to untreated furrows. This, coupled with prevention of pore blockage along the wetted perimeter, promotes greater lateral flow of PAM-treated water out and away from the furrow. Lentz et al. (1992) measured a 25% increase in the extent of lateral wetting (Fig. 1). These data were collected using shallow furrows between the rather flat beds of a field bean crop. Observation with furrow irrigated potatoes *(Sojka et al., 1995)* has shown that PAM effects cannot overcome use of deep furrows and pronounced beds (30 cm height) common in irrigated potato culture; lateral wetting extent in these cases was not measurably different between PAM-treated furrows and controls.

Figure 3. Effect of sediment concentration, measured in furrow water at the end of the first hour of irrigation, on final infiltration rate into a Portneuf silt loam as measured at 8 hr using recirculating infiltrometer. Data presented combine several treatment regimes.



Trout et al. (1995) confirmed that the infiltration benefit of PAM in irrigation water derived from the removal of sediment (Fig.2.). As sediment concentration of the flowing water declined, infiltration increased. This was true whether relating cumulative infiltration for the entire eight hours to mean sediment concentration of the initial hour, or relating final infiltration rate with initial sediment concentration (Fig. 3). The shape of the regression curve also reveals that for the Portneuf soil, irrigated with water of this quality, furrow stream sediment concentrations must be reduced to below about 3 to 5 g/L in order to mitigate the reduction of net infiltration rate from surface sealing. Optimal infiltration rates would require even lower values, perhaps half that concentration. Typical average seasonal runoff sediment concentrations of Pacific Northwest furrow irrigated land are about 15 g/L.

Furrow surface seals form when infiltration-reduced carrying capacity of the furrow stream causes deposition of transported sediments. Segeren and Trout (1991) showed that seals as thin as 0.2 mm could lower surface hydraulic conductivity two orders of magnitude below the conductivity of the parent soil. Sojka and Lentz (1994a) noted that PAM-treated furrows also form visibly identifiable surface seals, but postulated that these seals must be of a higher permeability than the seals in control furrows. They concluded this because net infiltration after 8-12 hrs of irrigation was significantly higher in PAM-treated furrows.

Ross et al. (1996) tested this hypothesis by comparing steady state infiltration of PAM-treated furrows and control furrows under slightly unsaturated conditions. Unlike the net infiltration and transient state infiltration rate data of the previously cited studies, the tension infiltrometer studies gave steady state values unaffected by changing water potential gradients within the soil profile. Furthermore, using water under slight tension allows an evaluation of water transmission through pores of specific equivalent diameters. That is, flow is excluded from the very large pores and fissures in this characterization of the infiltration process. Because all furrows presumably had the same surface pore geometry prior to irrigation, this measurement directly assesses the degree of seal formation that results from irrigation with untreated water vs PAM-treated water.

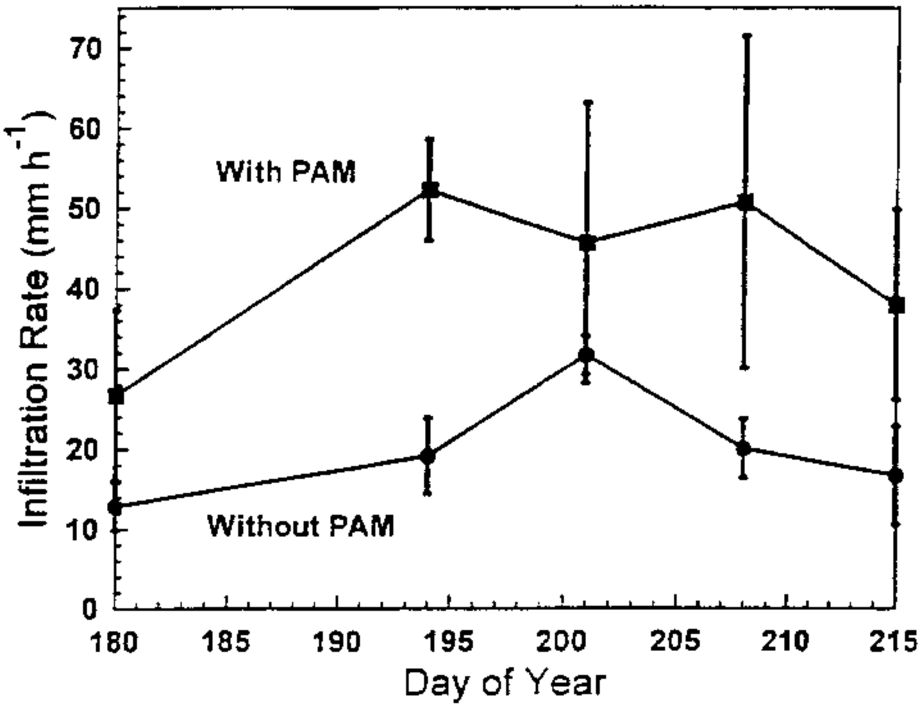
Figure 4 shows the steady state infiltration under 40 mm tension in furrow bottoms immediately following five consecutive irrigations in 1995. Each point is the mean of six determinations, with standard error displayed. Tension infiltration varies from one irrigation to the next, over a range of 12.9 to 31.8 mm/hr for controls and 26.7 to 52.2 mm/hr for PAM-treated furrows. This attests to the continuous shifting of fine deposits in the furrow with each irrigation. Nonetheless, the data show that in every case, the seals formed in PAM-treated furrows are about twice as permeable at 40 mm tension as the controls. Thus PAM-treated furrows have many more unblocked pores with equivalent mean spherical diameters of <0.75 mm over the irrigation season.

Similar data were obtained in several studies monitored in 1995. One study, had 1000 kg/ha PAM broadcast dry and rototilled into the plow layer of plots and was irrigated with PAM-treated water. Mean conductivities for two observation dates were 28.3 and 24.4 mm/h for 40 and 100 mm of tension respectively, irrigating with untreated water in control plots, compared to 69.2 and 55.9 mm/hr for irrigating with PAM-treated water in PAM-treated plots.

In assessing infiltration effects of PAM-use, some practical insights are of value. One determiner of furrow irrigation net infiltration is the size of the wetted perimeter. In PAM-treated furrows the furrow geometry is relatively stable throughout the season, and infiltration is not affected by variation in wetted perimeter. Without PAM-treatment, the gradual slaking of the furrow and/or deposition of eroded soil in the lower reaches of the field can result in a substantial increase of the wetted perimeter in all or part of the furrow length. These differences can result in a gradual equalization of net infiltration between treated and untreated furrows, or even an increase in net infiltration of controls late in the season. These wetted perimeter-determined changes can be localized, particularly at the outflow ends of furrows or on reaches where furrow slope abruptly decreases. Farmers using PAM may need to compensate seasonal irrigation practices to compensate for these effects.

One of the most dramatic benefits reported for PAM-use in farmer testimonials is the improved infiltration that occurs on "steep shoulders" or "breaking slopes." These refer to abrupt increases of slope occurring in only portions of fields. Untreated wa-

Figure 4. Steady state infiltration rate under 40 mm tension measured on furrow bottoms 24 hr following irrigation of a Portneuf silt loam on five dates in 1995. At this tension flow is only through pores smaller than 0.75 mm effective diameter.



ter tends to erode deep channels in these furrow portions. Infiltration is limited by the hastened flow and the small wetted perimeter of the deep channels. In addition, the lower elevation relative to the crop root structure limits such a furrow's ability to adequately supply water to the planted row. In this instance, PAM-treatment preserves adequate wetted perimeter and maintains the proper free water elevation (head) for transmission of water to the interrow. This is in addition to the seal effects noted earlier. Where steep furrow reaches are often unable to support adequate crop growth, PAM treatment has been reportedly able to sustain nearly normal uniform growth and yield. This is not an easy effect to study in replicated plots which are usually established in uniform, nearly optimal fields. Nonetheless, the effect is significant in providing economic incentive for PAM-use.

The single most important management consideration influenced by PAM's combined erosion-preventing and infiltration-increasing effects is the need to increase furrow inflow rates when PAM-treating. If PAM-treated inflows are not increased, the higher infiltration rate will delay stream advance relative to non-treated water. This would exacerbate one of furrow irrigation's greatest management drawbacks, namely the systematic non-uniformity of infiltration from upper to lower field ends induced by positional variation in infiltration opportunity time. Upper field reaches have longer infiltration opportunity time than lower field reaches. Since farmers usually irrigate to avoid stress at the lower field reach, this disuniformity usually results in over-irrigation of upper reaches.

Ideally, the increase of PAM-treated inflows should be substantial, for example doubling or tripling of the inflows. Data from Kimberly *(Sojka et al., 1995)* showed that when doubling PAM-treated inflows from 23 L/min to 45 L/min (4 gpm to 8 gpm) average advance rates across a 1.5 % sloping 175 m (570 ft.) field were 95 minutes for normal controls and 83 minutes for the higher PAM inflow rates, yet sediment lost from the high PAM inflows was only 24% of the untreated smaller inflows. All inflows in the study were cut back to 19 L/min once runoff began. The increased uniformity of the high-flow PAM-treated irrigation significantly improved Russet Burbank potato grade (market value) as well. Studies are currently underway to quantify leaching loss differences with PAM-use, which are expected to be reduced if PAM-use is coupled with higher inflows to improve field infiltration uniformity.

Conclusions

Polyacrylamide, used according to the NRCS standard, increases infiltration in addition to nearly eliminating furrow irrigation-induced erosion. The increase varies with several soil attributes, especially texture. Silt loam soils have shown about a 15% increase in net infiltration and a 25% increase in lateral wetting from shallow furrows between low flat beds. Fewer data are available for other textures, although limited reports suggest that the relative increase in net infiltration is larger for finer textured soils. The infiltration increase is enabled primarily by PAM's preservation of a more pervious pore structure during the formation of surface seals in furrows. If furrow inflows are not changed, PAM-use will prolong stream advance and exacerbate systematic furrow infiltration disuniformity from upper to lower field reaches. However, PAM's erosion preventing properties can be relied on to reduce erosion while greatly increasing inflow rates in order to significantly reduce stream advance rates and significantly improve infiltration uniformity along the furrow.

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